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By Richard C. Dingeldein, Andrew B. Connor, and David A. Hilton

April 1975

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16. Abstract

This paper summarizes the results of a study conducted for the Advanced Research Projects Agency and which assessed the extent to which practicable reductions of the external noise level of a number of aircraft could be achieved by relatively straightforward methods. The aircraft studied in this paper include the O-1, O-2, U-10, OV-1, and A-6.

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NOISE REDUCTION STUDIES OF SEVERAL AIRCRAFT TO REDUCE

THEIR AURAL DETECTION DISTANCE

By Richard C. Dingeldein, Andrew B. Connor,
and David A. Hilton

INTRODUCTION

At the request of the Advanced Research Projects Agency, the NASA-Langley Research Center has undertaken a study of the practicability of reducing the external noise of a number of airplanes by quick-fix methods not requiring major redesign of the aircraft. The utility of the suggested modifications is judged by their effect on the aural detection distance of the aircraft in cruising flight, as estimated using available procedures adapted to the requirements of this study. It is also important that the aircraft performance be penalized as little as possible.

The several fixed-wing airplanes for which meaningful improvements have been predicted are the subject of published Langley Working Papers (see refs. 1 through 5). The purpose of this paper is to summarize the results and the major conclusions of the overall study in one convenient reference.

A variety of propulsion systems is included. Reciprocating-engine propeller combinations are represented by the O-1, the U-10, and the Cessna Model 337 (O-2) aircraft. The OV-1 uses turbopropellers, and the A-6 is turbojet powered. The modifications studied have been limited to propeller and propeller-engine gearing changes, reciprocating-engine exhaust muffling, and the use of lobed turbojet-engine exhaust-noise suppressors.

This paper will summarize the noise signatures obtained from field measurements using the production aircraft and the signatures calculated to result from the modifications considered. In each case the estimated aural detection distance of the aircraft operating in low-speed cruising flight is also presented.

Some differences in the numerical results with those previously published reflect the improved data reduction and analysis procedures developed as the study progressed. The general conclusions, however, have not been significantly affected.

It is noted that three additional airplanes (the S-2F, AC-47, and P-2H) were originally included in the study. They do not appear in this summary paper because analysis indicated that low aural detection distances could not be realized by employing quick-fix methods.

This study represents the distillation of the efforts of a team of technical specialists assembled for this task from various elements of the Langley Research Center. The work of John L. Crigler (propellers); Tony L. Parrott, George M. Stokes, and Don D. Davis (exhaust mufflers); James L. Hassell, Jr. (aircraft performance); Maurice L. Sisson (weights); and Harvey H. Hubbard and Domenic J. Maglieri (acoustics) is especially acknowledged.

AIRCRAFT INCLUDED IN STUDY

The aircraft studied in this paper include the O-1, O-2, U-10, OV-1, and A-6. A photograph of each is shown in figure 1, and those characteristics important to this study are listed in table I. Additional information regarding each aircraft is given in references 1 through 5. A number of propulsion types are represented. The O-1, U-10, and O-2 are powered by reciprocating-engine propeller systems. The latter is a twin-engine aircraft using a tractor-pusher propeller arrangement. The OV-1 is a twin-turbopropeller aircraft, and the A-6 is a relatively large twin-turbojet-powered airplane.

EQUIPMENT AND PROCEDURES

Noise Measurement Procedures and Equipment

Static and flyover noise signatures from each airplane were recorded at the NASA Wallops Island test facility. A photograph of the test area is shown in figure 2. A weather station at the test site provided complete data on winds, temperature, and humidity during the noise measurements.

The microphones were equally spaced about the airplane for static noise measurements. The static data were recorded at the power conditions associated with the flyover tests. In the multiengine airplane cases, only one engine was operated during the static runs in order to facilitate identification of the discrete frequency components by narrow-band analyses. For the flyover measurements, the microphones were located along the ground track. Altitude and course over the recording equipment were obtained by a GSN/5 radar tracking unit for accurate positioning; course direction and altitude were maintained for at least 1 mile before and beyond the microphone position.

The noise measuring instrumentation for these tests is illustrated by the block diagram of figure 3. The microphones were of a conventional crystal type having a frequency response flat to within ±3 dB over the frequency range of 20 to 12,000 cps. The outputs of all the microphones at each station were recorded on multichannel tape recorders. The entire sound measurement system was calibrated in the field before and after the flight measurements by means of conventional discrete frequency calibrators supplied by the microphone manufacturers. The data records were played back from the tape (using the playback system shown in figure 3) to obtain the sound pressure level time histories and both broad-band and narrow-band spectra.

Methods of Analysis

The analysis procedure followed for each aircraft consisted first of identifying the dominant noise sources with the help of a narrow-band readout (3 cps bandwidth) of the noise tape. Next, available analytical procedures were employed to determine the noise contributions of modified components designed to provide lower noise levels. This required that a relatively large number of systematic design variations be studied. For example, it was not unusual to make calculations for 20 or more exhaust muffler-tailpipe configurations in attempts to quiet the reciprocating engines represented. The various components were assessed in different possible combinations representing increasing effectiveness and complexity, and a selection made of those to receive further study. For the modifications selected, the weight penalties were estimated, propeller efficiencies were calculated over the flight envelope, the aircraft performance was estimated, and a check was made to define possible problems relating to the flying and handling qualities of the modified aircraft. Finally, the aural detection distances corresponding to flight at different altitudes and over different types of ground cover were estimated using the procedures outlined in a previous section of this paper. The results of this analysis are believed to be representative of the amount of noise reduction that can be achieved by practicable modifications of the aircraft propulsion system, and of the type of hardware required to do the job. Obviously, other combinations of reduced-noise components may be equally feasible or even preferred to satisfy certain mission requirements.

It is noted that, in accordance with the ground rules set up at the start of this study, the noise analysis has been limited to the condition of low-speed cruising flight. However, an important consideration of the selection of the modifications studied has been to make them compatible with good aircraft efficiency over the entire flight envelope. This has largely been possible, as can be noted by reference to the tables presented later in the report which list some of the more important performance figures estimated for each aircraft.

Propulsion system noise reduction.- The propulsion system noise, which was the primary concern of this study, is treated extensively for the individual aircraft in references 1 to 5. The general approach to noise analysis is discussed in the following paragraphs.

For propeller-driven airplanes, the most important parameters to be considered in reducing the propeller noise are the propeller rotational tip speed and the number of blades. Experimental data (ref. 6) show that for a given design condition of engine power and airplane speed, the propeller noise can be reduced by a reduction in propeller tip speed and blade loading. The methods of references 6 and 7 were used in this study to estimate the sound pressure levels of the modified propellers considered. The performance parameters were selected to match the airplane's requirements by procedures described in references 7 to 10. Details on the propeller analysis for these airplanes are presented in references 1 to 4.

For reciprocating engines, the exhaust system is the main source of noise, and mufflers are required for noise reduction. Mufflers for engine-exhaust systems are perhaps more accurately described as low-pass acoustic filters designed to have a minimum impedance for steady volume flows and to have a high impedance for oscillating volume flows characteristic of acoustic waves. Reciprocating-engine exhaust noise is characterized by a discrete frequency spectrum. The frequency spectrum depends upon engine speed, number of cylinders, firing order, and exhaust manifold geometry as well as the exhaust mass-flow time history details of the individual cylinders.

The general procedure for muffler analysis is given in reference 11. Additional details relating to the muffler calculations made as part of this study are given in references 1 to 3.

The approach used to reduce the exhaust noise of the turbojet aircraft studied was the application of a corrugated or lobed exhaust nozzle as a device to increase the rate of jet exhaust mixing with the ambient air. This approach was based upon experimental results published in references 12 and 13, and its application to the specific airplane is given in reference 5.

Component weights and aircraft performance evaluations.- Changes in propeller weights were scaled as a function of volume and centrifugal force for aluminum alloys currently in use for propeller construction. Reduction gear weights were empirically derived from existing data on propeller reduction gears where weight versus output torque were plotted as a smooth curve on log-log coordinates. Detailed weight analyses for the various modifications are presented in references 1 to 5 which treat the specific airplanes and appropriate modifications such as nozzles, mufflers, hubs, and propellers.

Each modification was analyzed to determine the effect on performance and flying and handling qualities using classical analytical procedures. Further details relating to the estimates for each individual aircraft are given in references 1 to 5.

Determination of Aural Detection Distances

In addition to the noise source characteristics (see refs. 14 and 15), it is well known that the aural detection of a noise involves such factors as the transmission characteristics of the path over which the noise travels (refs. 16-20) and the acoustic conditions at the observer location (refs. 17 and 21), as well as the hearing ability of the observer (ref. 22). Attempts have been made to account for all of the pertinent factors in the above categories for the calculations of detection distance which follow.

Attenuation factors.- The attenuation factors associated with the transmission of noise from the source to the observer are assumed to involve the well-known inverse distance law, atmospheric absorption due to viscosity and heat conduction, small-scale turbulence, and terrain absorption which is weighted to account for the elevation angle between the source and the observer. For the purposes of this paper these factors are taken into account as determined by the following equation:

$$P.L.(f,x) = 20 \log_{10} \frac{x}{A} + \left[K_1 + K_2 + (K_3 - K_1)K_4\right]\frac{x}{1000}$$

where propagation loss (P.L.) is computed for each frequency and distance combination, and where the first term on the right-hand side of the equation accounts for the spherical spreading of the waves. In this connection, x is the distance for which the calculation is being made, and A is the reference distance for which measured data are available. The remaining terms which represent propagation losses and which are given in coefficient form are defined as follows:

K_1 represents the atmospheric absorption due to viscosity and heat conduction, and is expressed in dB per 1000 feet. The values of K_1 vary as a function of frequency and for the purposes of this paper are those of the following table. For frequencies up to 500 cps, data are taken from reference 16, and for the higher frequencies from reference 19.

Octave band no.	Center frequency	Decibel loss per 1000 feet
1	31.5	0.1
2	63	0.2
3	125	0.3
4	250	0.5
5	500	0.7
6	1000	1.4
7	2000	3
8	4000	7.7
9	8000	14.4

K_2 is the attenuation in the atmosphere due to small-scale turbulence. A value of 1.3 dB per 1000 feet is assumed independent of frequency for the frequency range above 250 cycles (see ref. 20).

K_3 also is expressed in dB per 1000 feet and includes both atmospheric absorption and terrain absorption. The values used are those of reference 17 which are listed for widely varying conditions of vegetation and ground cover. These data have been reproduced in a more convenient form in reference 18. Calculations included herein make use of the data of reference 18, particularly curve (b) of figure 1 which represents the condition of thick grass cover (18 inches high) and the upperbound of curve 3 of figure 2 which represents conditions of leafy jungle with approximately 100 feet "see through" visibility. The weighting factor K_4 is used to account for the angle, measured from the ground plane, between the noise source and the observer. The values of K_4 assumed for the present calculations were taken from figure 3 of reference 18 and are seen to vary from zero for angles greater than 7° to 1.0 for an angle of 0°.

Ambient noise level conditions and human hearing.- The detectability of a noise is also a function of the ambient masking noise conditions at the listening station and the hearing abilities of the listener. Since they are somewhat related, they will be discussed together.

The ambient noise level conditions assumed for these studies were based on data from references 17 and 21 which were obtained in jungle environments. The resulting octave-band spectra have been adjusted to account for critical bandwidth of the human ear, according to the following equation, to give masking level values for each band.

$$\text{Masking level, dB} = \text{octave band level, dB} - 10 \log_{10}\left[\frac{\Delta f_{octave}}{\Delta f_{critical}}\right]$$

where the Δf_{octave} and $\Delta f_{critical}$ values corresponding to standard octave band center frequencies are given in the following table:

Octave band center frequency, cps	31.5	63	125	250	500	1000	2000	4000	8000
Δf_{octave}, cps	22	44	88	177	354	707	1414	2828	5656
$\Delta f_{critical}$, cps	--	--	50	50	50	66	100	220	500
$10 \log_{10} \frac{\Delta f_{octave}}{\Delta f_{critical}}$	--	--	2.5	5.5	8.5	10.7	11.5	11.1	10.5

The values of the last line in the above table have been subtracted from the octave-band values to adjust them to the masking level spectra which define the boundaries of the jungle noise criteria detection region used in the subsequent determination of aural detection distances.

Likewise, a threshold of hearing curve (taken from ref. 16) is made use of since it represents the levels of pure-tone noise that are just detectable on the average by healthy young adults. The implication here is that noises having levels lower than those of the threshold of hearing curve at corresponding frequencies will not be detectable. Thus, the threshold of hearing curve is the determining factor of detection at the lower frequencies.

No attempt is made to account for possible binaural effects in the studies of the present paper.

The table presented below lists the reference jungle masking levels used in this study for estimating aural detection distances.

Octave band center frequency, cps	31.5	63	125	250	500	1000	2000	4000	8000
Ambient masking level for pure tones, dB	60 (a)	45 (a)	33.5	29	22.5	20	17.5	21	26
Ambient masking level for broad-band noise, dB	69 (a)	54 (a)	42.5 (a)	38	31.5	29	26.5	30	35

(a) These values based on the threshold of hearing.

Aural detection distance charts.- In the course of this study, it has been found very useful to express, in chart form and for a given aircraft altitude, the relationships between the attenuation of the aircraft noise from the atmospheric and terrain effects and the ambient background noise level adjusted for the masking effects previously discussed. This permits the aural detection distance in a given octave band to be quickly estimated, since the chart solves for the slant-range distance from the observer that is required to reduce the sound-pressure level of the source to the ambient masking level selected.

Such charts are presented in figure 4. The ordinate represents the difference in sound-pressure level in a given octave band, in decibels, between the noise source and the ambient masking level. Entering the chart with this difference and proceeding horizontally to the octave band for which this difference was taken, the aural detection distance is read off on the abscissa. The octave-band center frequencies are plotted for the two ground-cover conditions analyzed in this task; namely, 18-inch grass and a rather dense jungle having an average see-through distance of 100 feet.

Figure 4(a) has been prepared for an aircraft flying at an altitude of 300 feet and requires the aircraft noise signature, by octave bands, to be known for a distance of 300 feet. Figure 4(b) is for an aircraft altitude of 1000 feet, and requires the aircraft signature at a distance of 1000 feet to be known.

RESULTS AND DISCUSSION

In this summary of the previously published working papers (refs. 1 to 5), each aircraft will be considered in turn. The contributions of the major noise sources identified from the measurements made in the field are listed by octave band for the propeller-driven aircraft. The modifications studied for all the aircraft and their estimated effect on the noise signature, aural detection distance, and aircraft performance are presented. Details relating to the analysis procedures are provided in the original working papers just referred to, and will not be repeated here.

O-1 Aircraft

The O-1A aircraft, for which the basic reference sound-pressure levels were obtained, is equipped with a fixed-pitch propeller. Unlike reference 1, the modifications discussed in this paper are all confined to the use of controllable-pitch propellers, which permit higher efficiency to be realized over the entire flight envelope.

The operating condition selected for obtaining the O-1 noise measurements and analyzing the noise-reduction potential for this aircraft was flight at 105 mph and 2250 engine rpm.

The noise contributions of the basic O-1A propeller and engine in the four lower octave bands (center frequencies of 31.5, 63, 125, and 250 cycles per second, corresponding to bands defined from 22-44, 44-88, 88-177, and 177-354 cycles per second, respectively) are listed in table II for a distance of 300 feet. Also given are the estimated noise contributions of three of the quieter propellers analyzed, as well as those for the engine equipped with three different single-chamber resonator-type exhaust mufflers. These modified components were combined as indicated in table III. Note that, in addition to the three modifications reported in reference 1, a revised Modification I has been included in this paper. A check of the combined noise contributions of the engine and propeller components indicated that a better matching of these items would be afforded by using the 1.54-ft^3 muffler with the Modification I propeller. This is apparent from the sound-pressure levels presented in table II, and effectively makes the point that the most effective design practice will attempt to reduce the noise contributions of the individual components to roughly the same level.

The estimated effect of Modifications I, II, and III on the aircraft performance is summarized in table IV. There is relatively little change associated with Modifications I and II (Modification I-Revised will be essentially the same as Modification I), however, the relatively large weight increase associated with Modification III adversely affects the takeoff and climb performance.

The distribution of sound-pressure level in the various octave bands at a distance of 300 feet is presented in figure 5 for the basic O-1 aircraft and for each of the four modifications shown in table III. The signature of the basic aircraft was obtained from flyover measurements at an altitude of 570 feet and corrected to the 300-foot reference distance. The sound-pressure levels in the four lower octave bands shown for the modifications represent the additive effects of the estimated noise from the modified propellers and muffled engines. The differences between this figure and the results presented in reference 1 are largely the result of correcting the basic noise measurements for the recording system response at the lower end of the frequency range.

The noise in the fifth and higher octave bands consists of a wide range of random frequencies to which the propeller vortex noise is an important contributor. This latter noise energy is shown in reference 23 to vary as the sixth power of the tip speed and the first power of the total propeller blade area. The dependence of the sound-pressure level, which is the quantity dealt with in this paper, is as the square root of this energy dependence. The estimated sound-pressure levels for the different modifications of this and succeeding aircraft in the fifth and higher octave bands were obtained by adjusting the measured data to account for the change in vortex noise associated with the geometry and tip speed of the modified propellers.

Substantial reductions in the sound-pressure levels are indicated in figure 5 for all the modifications in the lower octave bands, which experience has shown are usually the critical ones in determining the aural detection distance. The aural detection distances estimated for flight at altitudes of 300 and 1000 feet over 18-inch grass or leafy jungle terrain are given in table V. Substantial reductions in the aural detection distance are provided by all the modifications, although the most efficient appears to be Modification I-Revised. Here, for an estimated net weight increase of only 34 pounds and without requiring engine-propeller gearing, the aural detection distances for the four combinations of aircraft altitude and ground cover considered are reduced to values ranging from 28 to 66 percent of those for the basic aircraft. Further reductions are indicated for Modification III, which is considered representative of the most that could be accomplished with this aircraft by means of propeller changes and engine-exhaust mufflers. The minimum detection distances for Modification I-Revised and Modification III are estimated for the O-1 aircraft flying at 300 feet over dense jungle to be approximately 5900 feet and 4800 feet, respectively.

U-10 Aircraft

Unlike the other aircraft reported in this paper, an opportunity was provided to measure the U-10B noise signatures for the basic aircraft and for the aircraft equipped with an experimental 1.3-ft^3 muffler made available by the manufacturer. Also, because of the interest in the probability of achieving substantial propeller noise reductions by a drastic reduction in the engine speed, data were obtained for different engine operating conditions (see ref. 2). The measurements are summarized in figure 6, which shows the noise signatures measured for the unmodified or basic aircraft with the engine operating at 2750 and 1650 rpm, and the effect of installing the experimental muffler. It is noted that the 1650 rpm condition is well outside the operating range of this engine as specified by its manufacturer. The figure shows that the muffler successfully reduced the engine noise contribution, and these signatures will be interpreted in terms of the estimated reduction in the aural detection distance later in this section.

The noise contributions determined for the basic U-10 engine and propeller from flight measurements at an engine speed of 2750 rpm, 166 shaft horsepower, and 133 mph are presented in table VI. Also included for the same operating condition are the noise estimates predicted for the engine equipped with a 2-ft^3 double-expansion chamber muffler (tailpipe length = 3.63 feet) and for two propeller modifications, the second of which requires a change in the engine/propeller gear ratio. The modifications selected for analysis are briefly described in table VII, and the negligibl effect predicted with respect to aircraft performance is apparent from inspection of table VIII.

The noise signatures estimated for Modifications I and II are compared with that for the unmodified aircraft in figure 7.

The estimated aural detection distances for the basic U-10 aircraft operating at 2750 and 1650 rpm, and the aircraft with the experimental muffler installed (1650 rpm) are given in table IX, along with the results anticipated for Modifications I and II. No advantage is seen to result from operating the engine on the unmodified aircraft at 1650 rpm. Although this condition also represents reduced power, the reduced speed effectively crowds more of the engine firing frequencies into the second octave band (see fig. 6), substantially raising the noise level and adversely affecting the aural detection distance. Installation of the experimental muffler is seen to reduce the estimated detection distance to a minimum of 6100 feet for flight at 300 feet over a dense jungle. Substantial reductions are also indicated for Modifications I and II, with minimum detection distances of 6400 and 4700 feet, respectively, noted for the aforementioned flight condition.

O-2 Aircraft

Although no O-2 aircraft was available for the study, noise measurements were obtained on a Cessna Model 337 aircraft supplied by the manufacturer. Inasmuch as this aircraft is expected to be identical to the O-2A as a noise source, the service designation has been used throughout this report.

Because of its tractor-pusher powerplant arrangement, the O-2 aircraft can be flown with only the front or the rear engine, or with both engines operating. Reference 3 shows essentially the same noise signature in the five lowest octave bands for flight at approximately the same total shaft horsepower using only the front engine or both engines. Flight at the same airspeed (in the vicinity of 100 mps) using only the rear engine shows lower noise levels in the third octave band (center frequency = 125 cps). This is primarily because the production aircraft incorporates a small (0.45 ft^3) exhaust muffler on the rear engine. A secondary cause of reduced noise associated with rear-engine only operation is that less power is required to fly at a given airspeed, probably as a result of lower drag associated with reduced airflow separation in the vicinity of the fuselage-wing-tailboom junctures. For the purposes of this analysis, twin-engine operation was assumed to be required. The condition selected for the noise-reduction analysis was flight at 2400 rpm, 1?0 total shaft horsepower, and 104 mph.

The distribution of the measured engine and propeller sound-pressure levels in the various octave bands is presented in table X. The values were obtained from measurements of the front engine-propeller combination operating at 120 horsepower, which is taken to be the same as two units, perfectly synchronized, operating at the same total horsepower. Also shown are the calculated contributions, by octave bands, of the engine equipped with three different mufflers. Two propellers designed to provide efficient performance and low noise level are also included. The muffled engine-propeller combinations selected as typical of the noise reductions practicable for the O-2 aircraft are briefly summarized in table XI. Two different muffler-tailpipe arrangements are combined with the six-blade, reduced-diameter, ungeared propeller to give Modifications IA and IB. These mufflers are single-chamber resonators. The front muffler is mounted externally on the belly of the aircraft, the rear mufflers appear capable of being fitted inside the engine compartment. Modification II requires a 0.75:1 propeller/engine gear box, a six-blade propeller of standard diameter, and a double-expansion chamber muffler of about 50 sq in. cross section and 10 feet long. The mufflers for the front and rear engines can be nested together alongside the fuselage in a single package as noted in table XI. Some provision, such as a conical shield, would have to be made to prevent ram air from entering the forward-pointing exhaust of the rear-engine muffler.

Modification II is believed representative of the maximum noise reduction practicable without a major research and development effort on this aircraft. The estimated effect of the foregoing modifications on the aircraft performance is given in table XII, and is noted to be small. The noise signatures measured in low-speed cruising flight with both engines operating, and with the rear engine only, are presented in figure 8, along with the estimated noise spectrum for the different modifications analyzed. Large reductions in the sound-pressure levels are indicated for the modified aircraft. Although it will not be discussed in detail, it is noted that a substantial part of the reduction predicted for Modification IB compared to Modification IA results from the longer tailpipe used (2.65 feet compared to 1.0 foot). This provides larger attenuation for the muffler-tailpipe combination at the lower frequencies, which are the troublesome ones from the standpoint of aural detection. It also emphasizes the fact that the tailpipe length must be considered in any evaluation of muffler performance.

The aural detection distances estimated for the noise signatures of figure 8 are listed in table XIII. Little difference is noted for the basic aircraft between the two modes of engine operation.

The modifications studied are indicated to reduce the aural detection distance to a minimum value of slightly less than 1 mile (Modification II) for flight at 300 feet over 18-inch grass or dense jungle terrain cover, compared to 3.8 and 1.65 miles, respectively, for the basic aircraft.

OV-1 Aircraft

The OV-1A aircraft is powered by two turbopropeller engines. Analysis of the narrow-band readout of the noise tapes obtained on the basic aircraft showed high-intensity pure tones associated with the propeller blade passage frequency and integral multiples thereof (see ref. 4). The engine noise was of the broadband type having sound-pressure levels far below the dominant propeller noise. Inasmuch as the engine noise for the low-speed cruising flight condition selected was therefore not expected to be an important factor in defining the aural detection distance for this aircraft, no engine modifications were considered.

The sound-pressure levels, by octave bands, measured for the OV-1 propeller are presented in table XIV, along with the calculated noise contributions of three five- and six-blade propellers, two of which require a change in the gearing between the power turbine and the propeller shaft. The flight condition selected for analysis and for which flyover octave-band spectra were obtained, corresponds to a propeller speed of 1200 rpm, 652 shaft horsepower (two engines), and an airspeed of 140 knots. The modifications studied are described in table XV. The effect of these modifications on the performance of the OV-1 aircraft is estimated to be small (see table XVI).

The noise signatures estimated for the OV-1 modifications studied are compared with that measured for the basic aircraft in figure 9. The calculated signatures consider that the noise from the two propellers is perfectly in phase, and thus the total propeller noise contribution is 6 dB greater than that estimated for a single propeller. The corresponding estimated aural detection distances are listed in table XVII. The fact that the engine noise contribution is distributed as low-level broadband noise over the frequency range rather than as high-intensity, pure tones (as is the case for reciprocating engines) results in rather low detection distances compared to what might be expected for reciprocating-engine aircraft of similar installed power. Table XVII indicates aural detection distances ranging from slightly less than 1 mile to about 1-3/4 miles for the combinations of aircraft altitude and terrain cover considered.

A-6 Aircraft

The EA-6A aircraft for which noise measurements were obtained is powered by two turbojet engines. It is capable of high subsonic speeds and is large in comparison with the propeller-driven aircraft studied thus far. As noted in reference 5, the measured noise signatures indicated that the main source of noise is the mixing of the jet engine exhausts with the surrounding air. One approach to reducing this jet exhaust noise is to increase the physical size of the region where this mixing takes place, and there has been considerable research on the effect of using lobed or corrugated exhaust nozzles to increase the jet exit perimeter (see, for example, ref. 12). Fortunately for the analysis of the A-6 aircraft, work done at the NASA-Lewis Flight Propulsion Laboratory on an aircraft having engines of similar characteristics and installation as the A-6 is directly applicable (see ref. 13, and see discussion in appendix D of ref. 5). Accordingly, the average noise attenuation measured for the eight-lobe jet-exhaust suppressor in the different octave bands in these tests was directly applied to the basic noise signature measured for the A-6 aircraft. A schematic sketch of the installation considered for the A-6 aircraft is shown in figure 10. Inasmuch as the aural detection distance is usually determined by the sound-pressure levels in the lower octave bands, for which greater noise attenuation can be expected for a jet-exhaust suppressor having fewer lobes, the results of reference 12 were used to estimate the attenuation of a four-lobe suppressor. Table XVIII summarizes the estimated effect of installing four- and eight-lobe suppressors on the A-6 aircraft. Nominal weight increases of less than 200 pounds for this 55,000-pound aircraft are predicted. The effect on performance for the condition of two-engine military power is listed in table XIX. The most adverse effect is to increase the estimated takeoff distance to clear a 50-foot obstacle by 5 percent.

The signatures based on measurements of the unmodified A-6 aircraft and predicted when the four- and eight-lobe jet-exhaust suppressors are installed are presented in figure 11 for a distance of 1000 feet. The reference flight condition is cruise at 335 knots. The corresponding estimated aural detection distances are shown in table XX. The minimum aural detection distance is estimated to be 6600 and 6900 feet, respectively, for the four- and eight-lobe suppressors installed, and with the aircraft flying at 300 feet over dense jungle. These detection distances increase to a value of about 2-1/4 miles with the aircraft at an altitude of 1000 feet.

General Comments on Results

For the low-speed cruising flight conditions represented in this study, some generalization of the foregoing results may be of interest.

Propeller changes and engine exhaust muffling are predicted to significantly reduce the overall external aircraft noise and the resulting aural detection distance with only modest effects on the aircraft weight and performance.

The overall sound-pressure levels determined for the basic propeller-driven aircraft at a reference distance of 300 feet ranged from 92 to 97 dB. All-out attempts to quiet the propeller by reducing tip speed (gearing change) and increasing the number of blades, together with the use of exhaust mufflers on the reciprocating engines represented, are estimated to reduce these sound-pressure levels by nearly 20 dB. Reductions of 10 dB, however, appear relatively easy to accomplish for these aircraft without changing the propeller/engine speed ratio by using five- or six-blade propellers of reduced diameter in conjunction with engine exhaust mufflers.

An overall noise reduction for the turbojet airplane of approximately 8 dB is forcast by the use of multilobed exhaust noise suppressors.

The maximum noise reductions calculated for all the propeller aircraft (that is, the O-1, U-10, O-2, and OV-1 airplanes) operating at an altitude of 300 feet over dense jungle are predicted to reduce the aural detection distance to approximately 5000 feet. For the simpler modifications (that is, no propeller/engine gearing change), the corresponding detection distance is estimated to lie in the range from approximately 6000 to 7000 feet. Increasing aircraft altitude from 300 feet to 1000 feet over dense jungle approximately doubles the estimated aural detection distance. The reduced sound absorption provided by 18-inch grass ground cover results in a minimum increase in the aural detection distance of roughly 50 percent over that predicted for the dense jungle ground cover for both altitudes considered.

If aural detection distances appreciably less than 1 mile are required for a particular mission, it will be necessary to include noise considerations in the initial design of the aircraft.

CONCLUDING REMARKS

This paper summarizes the results of a study conducted for the Advanced Research Projects Agency and which assessed the extent to which practicable reductions of the external noise level of a number of aircraft could be achieved by relatively straightforward methods.

The sound-pressure levels measured for the unmodified aircraft in low-speed cruising flight are presented, along with the estimated noise signatures associated with propeller changes and engine exhaust muffling. The results are interpreted in terms of the estimated aural detection distance of the aircraft.

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TABLE I.- AIRCRAFT CHARACTERISTICS

Aircraft	Airframe		Powerplant						Propeller			
	Gross Weight, LB.	Wing Area, FT^2	Number	Type	Cylinders	Displacement, IN^3	Takeoff Rating HP/RPM	Normal Rating HP/RPM	Diameter, IN.	No. of Blades	Gear Ratio Prop.:Engine	Solidity per Blade (.7 Radius)
O-1	2100	174	1	Recip.	6	470	213/2600	190/2300	90	2	1:1	0.035
U-10	3000	251	1	Recip.	6	480	295/3400	280/3000	96	3	77:120	.0295
O-2	4200	201	2	Recip.	6	360	210/2800	210/2800	76	2	1:1	.034
OV-1	12148	330	2	Turbo-Prop.	—	—	1100 Shaft H.P.	900 Shaft H.P.	120	3	1:124	.038
A-6	55060	529	2	Turbo-Jet	—	—	8500 LB. Static Thrust (100% RPM)	8000 LB. Static Thrust (96% RPM)	—	—	—	—

TABLE II.- SOUND PRESSURE LEVELS OF MAJOR O-1 NOISE SOURCES, dB

DISTANCE = 300 FEET

NOISE SOURCE	OCTAVE BAND CENTER FREQUENCY, CPS			
	31.5	63	125	250
BASIC O-1A ENGINE @ 2250 RPM (MEAS.)	62.4	83.2	86.1	81.6
ENGINE + 0.725 FT^3 MUFFLER (CALC.)	59.4	71.0	72.5	81.2
ENGINE + 1.54 FT^3 MUFFLER (CALC.)	60.4	69.1	66.2	71.6
ENGINE + 6.15 FT^3 MUFFLER (CALC.)	63.4	69.5	62.7	62.9
BASIC PROPELLER (MEAS.)	—	77.9	78.9	81.1
MOD. I PROPELLER (CALC.)	—	—	—	76.8
MOD. II PROPELLER (CALC.)	—	—	69.9	47.5
MOD. III PROPELLER (CALC.)	—	—	60.3	25.7

TABLE III.- SUMMARY OF O-1 MODIFICATIONS

Configuration	Propeller						Muffler [a]			Tail-Pipe Length ft.	Net Weight Increase lb.	Overall Sound Pressure Level @ 300 ft. dB
	Gear Ratio Prop.:Engine	Prop. RPM	Diameter in.	No. of Blades	Solidity per Blade (0.7 radius)	Type	Dia. & Length in.	Volume ft³	Location			
Basic O-1A	1:1	2250	90	2	0.035	Fixed Pitch	—	—	—	—	—	95.2
Mod. I	1:1	2250	78	6	.0203	Control'ble Pitch	7.5 x 31.6	0.725	External [b]	1.67	25	84.7
Mod. I-Rev.	1:1	2250	78	6	.0203	Control'ble Pitch	9.7 x 38.8	1.54	External [b]	1.67	34	82.1
Mod. II	2:3	1500	90	5	.035	Control'ble Pitch	9.7 x 38.8	1.54	Internal [c]	2.89	115	78.7
Mod. III	1:2	1125	90	5	.056	Control'ble Pitch	19 x 26	6.15	Internal [c]	2.89	255	74.2

[a] SINGLE - CHAMBER RESONATOR

[b] BENEATH FUSELAGE BETWEEN LANDING GEAR STRUTS

[c] INSIDE FUSELAGE AFT OF PASSENGER COMPARTMENT

TABLE IV.- ESTIMATED SEA-LEVEL PERFORMANCE OF THE O-1 AIRCRAFT

ITEM	BASIC AIRCRAFT	MOD. I	MOD. II	MOD. III
GROSS WEIGHT, LB.	2100	2125	2215	2400[a]
TYPE OF PROPELLER (FIXED OR CONTROLLABLE PITCH)	FIXED	CONTROLLABLE	CONTROLLABLE	CONTROLLABLE
TOTAL DISTANCE TO CLEAR 50 FT OBSTACLE, FT.	550	531	552	763
GROUND RUN, FT.	311	293	302	415
RATE OF CLIMB, FT/MIN.	1291	1300	1295	1090
MAXIMUM SPEED, KTS.	115.9	115.5	115.8	115
STALLING SPEED, KTS.	36.5	36.7	37.7	39.4
CRUISE SPEED, KTS.	78	80	80	80
SPEED FOR BEST RATE OF CLIMB, KTS.	58	58	59	60

[a] INCLUDES 45 LB. BALLAST AT TAIL POST TO KEEP AIRCRAFT CENTER OF GRAVITY WITHIN ALLOWABLE LIMITS

TABLE V.- ESTIMATED AURAL DETECTION DISTANCE FOR THE O-1 AIRCRAFT, IN FEET FROM OBSERVER

Flight Condition		Basic O-1	Mod. I	Mod I-Rev	Mod. II	Mod III
Altitude, ft	Ground Cover					
300	18-in. grass	25 000 [a 2]	8400 [3]	6900 [4]	8000 [3]	6000 [3]
	Leafy jungle	5300 [3]	6300 [4]	5900 [4]	6000 [3]	4800 [3]
1000	18-in. grass	26 800 [3]	13 500 [3]	9900 [4]	12700 [3]	8200 [3]
	Leafy jungle	16000 [3]	10 800 [3]	9400 [4]	10500 [3]	8200 [3]

[a] Denotes critical octave band

TABLE VI.- SOUND PRESSURE LEVELS OF MAJOR U-10 NOISE SOURCES, dB

DISTANCE = 300 FT

NOISE SOURCE	OCTAVE BAND CENTER FREQUENCY, CPS.			
	31.5	63	125	250
BASIC U-10 ENGINE @ 2750RPM, 166HP (MEAS.)	—	69.4	93.4	83.1
ENGINE + 2 FT^3 MUFFLER (CALC.)	—	59.4	63.7	56.2
BASIC PROPELLER (MEAS.)	—	—	88.6	75.5
MOD. I PROPELLER (CALC.)	—	—	73.4	53.5
MOD. II PROPELLER (CALC.)	—	61.4	29.4	—

TABLE VII.- SUMMARY OF U-10 MODIFICATIONS

CONFIGURATION	PROPELLER					MUFFLER[a]		TAIL-PIPE LENGTH FT	NET WEIGHT INCREASE LBS	OVERALL SOUND PRESSURE LEVEL @ 300 FT dB
	GEAR RATIO PROP:ENGINE	PROP. RPM	DIAMETER IN.	NO. OF BLADES	SOLIDITY PER BLADE (0.7 RADIUS)	DIA & LENGTH IN	VOLUME FT^3			
BASIC U-10	77:120	1765	96	3	0.0295	—	—	—	—	97
MOD. I	77:120	1765	84	5	.0265	7.5x80	2	3.63	17	83
MOD. II	44:120	1008	108	5	.0274	7.5x80	2	3.63	100	78

[a] DOUBLE EXPANSION CHAMBER

TABLE VIII - ESTIMATED PERFORMANCE OF THE U-10 AIRCRAFT

ITEM	BASIC AIRCRAFT	MOD. I	MOD. II
GROSS WEIGHT, LBS	3000	3017	3100
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	520	553	549
TAKE-OFF GROUND RUN, FT.	236	252	246
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	1460	1408	1431
5000 FT.	1120	1079	1098
10 000 FT.	816	781	789
SERVICE CEILING @ NORMAL RATED POWER, FT.	21 100	20 700	20 700
SPEED FOR BEST RATE OF CLIMB, KTS, @ SEA LEVEL	80	86	81
5000 FT.	85	86	86
10 000 FT.	86	87	88
MAXIMUM SPEED, KTS, @ SEA LEVEL	143	143	144
5 000 FT.	141	141	142
10 000 FT.	139	139	139

TABLE IX.- ESTIMATED AURAL DETECTION DISTANCE FOR THE U-10 AIRCRAFT, IN FEET FROM OBSERVER

Flight Condition		Basic U-10		With experimental muffler	Mod. I	Mod. II
Altitude, ft.	Ground Cover	2750 RPM	1650 RPM	1650 RPM		
300	18-in. grass	21 500 [a] [2]	41 000 [2]	12000 [2]	8900 [3]	5800 [3]
	Leafy jungle	9600 [3]	9100 [2]	6100 [2]	6400 [3]	4700 [3]
1000	18-in. grass	28100 [3]	41000 [2]	13200 [3]	14400 [3]	7[illegible]00 [5]
	Leafy jungle	17000 [3]	16200 [2]	10600 [3]	11200 [3]	7700 [5]

[a] Denotes critical octave band

TABLE X - SOUND PRESSURE LEVELS OF MAJOR O-2 NOISE SOURCES, dB

DISTANCE = 300 FT.

NOISE SOURCE	OCTAVE BAND CENTER FREQUENCY, CPS			
	31.5	63	125	250
BASIC ENGINE @ 2400 RPM, 120 HP (MEAS.)	70.9	90.1	92.4	88
ENGINE + 2.22 FT^3 MUFFLER (CALC.)	77.4	75.9	74.9	72.8
ENGINE + 3.33 FT^3 MUFFLER (CALC.)	62.4	62.9	65.4	73.3
ENGINE + 3.49 FT^3 MUFFLER (CALC.)	69.4	69.5	59.2	51.3

BASIC PROPELLER (MEAS.)	—	80.9	78.9	76.6
MOD. I PROPELLER (CALC.)	—	—	—	70.7
MOD. II PROPELLER (CALC.)	—	—	—	63.6

TABLE XI.- SUMMARY OF O-2 MODIFICATIONS

CONFIGURATION	PROPELLER					MUFFLER		TAIL-PIPE LENGTH FT	NET WEIGHT INCREASE LB	OVERALL SOUND PRESSURE LEVEL @ 300 FT. dB
	GEAR RATIO PROP:ENGINE	PROP. RPM	DIAMETER IN.	NO. OF BLADES	SOLIDITY PER BLADE (0.7 RADIUS)	DIA. & LENGTH IN.	VOLUME FT^3			
BASIC O-2	1:1	2400	76	2	0.034	a	0.45	0.42		92
MOD. IA	1:1	2400	64	6	.0215	12× 36	2.22 b	1	16	82
MOD. IB	1:1	2400	64	6	.0215	13×46	3.33 b	2.65	43	80
MOD. II	3:4	1800	76	6	.018	d	3.49 c	1	117	78

a STANDARD EQUIPMENT ON REAR ENGINE ONLY, OVAL SHAPE APPROXIMATELY 4.6×12.6 IN., AND 16 IN. LONG

b SINGLE CHAMBER RESONATOR

c DOUBLE EXPANSION CHAMBER

d MUFFLERS FOR EACH ENGINE COMBINED INTO ONE PACKAGE HAVING OVAL CROSS SECTION (6.6× 19.8 IN) AND 120 IN. LONG

TABLE XII. - ESTIMATED PERFORMANCE OF THE O-2 AIRCRAFT

ITEM	BASIC AIRCRAFT	MOD. I A	MOD. I B	MOD. II
GROSS WEIGHT, LB.	4200	4216	4243	4317
TOTAL DISTANCE TO CLR. 50 FT. OBSTACLE, FT.	1435	1505	1515	1500
TAKE-OFF GROUND RUN, FT.	805	840	850	860
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	1305	1270	1260	1270
5000 FT.	1010	975	970	986
10 000 FT.	715	680	675	685
SERVICE CEILING @ NORMAL RATED POWER, FT	20 500	20 000	20000	20300
SPEED FOR BEST RATE OF CLIMB, KTS, @ SEA LEVEL	93	93	94	94
5000 FT.	98	98	98	99
10 000 FT.	103	103	103	104
MAXIMUM SPEED, KTS, @ SEA LEVEL	174	172	172	172
5000 FT.	172	170	170	170
10 000 FT.	168	166	166	166

TABLE XIII.- ESTIMATED AURAL DETECTION DISTANCE FOR THE O-2 AIRCRAFT, IN FEET FROM OBSERVER

FLIGHT CONDITION		BASIC O-2		MOD. I A	MOD. I B	MOD. II
ALTITUDE, FT.	GROUND COVER	FRONT & REAR ENGINES	REAR ENGINE ONLY			
300	18-IN. GRASS	20000[a,2]	23300[2]	9200[3]	6550[4]	5100[5]
	LEAFY JUNGLE	8700[3]	7800[3]	6600[3]	5600[4]	4800[5]
1000	18-IN. GRASS	23400[3]	23500[2]	14900[3]	9100[4]	7700[5]
	LEAFY JUNGLE	15200[3]	13800[3]	11500[3]	8900[4]	7700[5]

[a] DENOTES CRITICAL OCTAVE BAND

TABLE XIV.- SOUND PRESSURE LEVEL OF OV-1 PROPELLER NOISE, dB

DISTANCE = 300 FT.

CONFIGURATION	OCTAVE BAND CENTER FREQUENCY, CPS			
	31.5	63	.25	250
BASIC SINGLE PROPELLER (MEAS.)	—	87.9	75.9	71.6
MOD. I PROPELLER (CALC.)	—	—	71.9	49.2
MOD. II PROPELLER (CALC.)	—	64.9	34.0	—
MOD. III PROPELLER (CALC.)	—	55.3	—	—

TABLE XV.- SUMMARY OF OV-1 MODIFICATIONS

CONFIGURATION	PROPELLER					NET WEIGHT INCREASE LB	OVERALL SOUND PRESSURE LEVEL @ 300 FT. dB
	GEAR RATIO PROP:ENGINE	PROP. RPM	DIAMETER IN.	NO. OF BLADES	SOLIDITY PER BLADE (.7 RADIUS)		
BASIC OV-1	1:12.4	1200	120	3	0.0381	—	93.3
MOD. I	1:12.4	1200	108	5	.0343	−22	81.5
MOD. I	1:16.53	900	120	5	.0381	129	77.1
MOD. III	1:17.71	840	120	6	.0343	82	75.2

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TABLE XVI - ESTIMATED PERFORMANCE OF THE OV-1 AIRCRAFT

ITEM	BASIC AIRCRAFT	MOD. I	MOD. II	MOD. III
GROSS WEIGHT, LB	12 148	12 126	12 277	12 230
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	1 073	1 116	1 165	1 146
TAKE-OFF GROUND RUN, FT.	723	765	810	783
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	2416	2383	2325	2328
10 000 FT.	1748	1713	1668	1671
20 000 FT.	995	976	935	943
SERVICE CEILING, FT.	29 300	29 300	28 800	28 800
SPEED FOR BEST RATE OF CLIMB, KTS., @ SEA LEVEL	139	139	139	139
10 000 FT.	144	144	146	145
20 000 FT.	156	156	157	157
MAXIMUM SPEED, KTS., @ SEA LEVEL	242	242	241	241
10 000 FT.	249	249	248	248
20 000 FT.	245	245	244	244

TABLE XVII - ESTIMATED AURAL DETECTION DISTANCE FOR THE OV-1 AIRCRAFT, IN FEET FROM OBSERVER

Flight Condition		Basic OV-1	Mod. I	Mod. II	Mod. III
Altitude, ft.	Ground Cover				
300	18-in. grass	30 000 $^{a\,2}$	10300 ^{3}	6700 ^{3}	6300 ^{3}
	Leafy jungle	8450 ^{3}	7100 ^{3}	5200 ^{3}	5000 ^{3}
1 000	18-in. grass	30300 ^{2}	17400 ^{3}	9800 ^{3}	9200 ^{3}
	Leafy jungle	14800 ^{2}	12500 ^{3}	9100 ^{3}	8600 ^{3}

^{a} DENOTES CRITICAL OCTAVE BAND

TABLE XVIII - SUMMARY OF A-6 MODIFICATIONS

CONFIGURATION	SUPPRESSOR GEOMETRY	NET WEIGHT INCREASE, LB	OVERALL SOUND PRESSURE LEVEL (@ 1000 FT.), dB
BASIC A-6	—	—	91
MOD. I	4-LOBE	155	85
MOD. II	8-LOBE	199	83.3

TABLE XIX.- ESTIMATED PERFORMANCE OF THE A-6 AIRCRAFT [a]

ITEM	BASIC AIRCRAFT	MOD. I (4-LOBE)	MOD. II (8-LOBE)
TAKE-OFF GROSS WEIGHT, LB.	55 060	55 216	55 219
TOTAL DISTANCE TO CLEAR 50 FT. OBSTACLE, FT.	6 070	6 220	6 310
TAKE-OFF GROUND RUN, FT.	5 350	5 480	5 560
WEIGHT, LB.	54 118	54 278	54 317
RATE OF CLIMB, FT/MIN, @ SEA LEVEL	5 050	4 920	4 860
15 000 FT	2860	2740	2680
25 000 FT	1450	1340	1290
SERVICE CEILING, FT	33 800	33 000	32 800
SPEED FOR BEST RATE OF CLIMB, KTS, @ SEA LEVEL	344	333	327
15000 FT	372	366	362
25 000 FT	391	387	385
MAXIMUM SPEED, KTS, @ SEA LEVEL	522	511	506
15 000 FT	515	508	505
25 000 FT	492	486	484

[a] J 52-P-6A ENGINES

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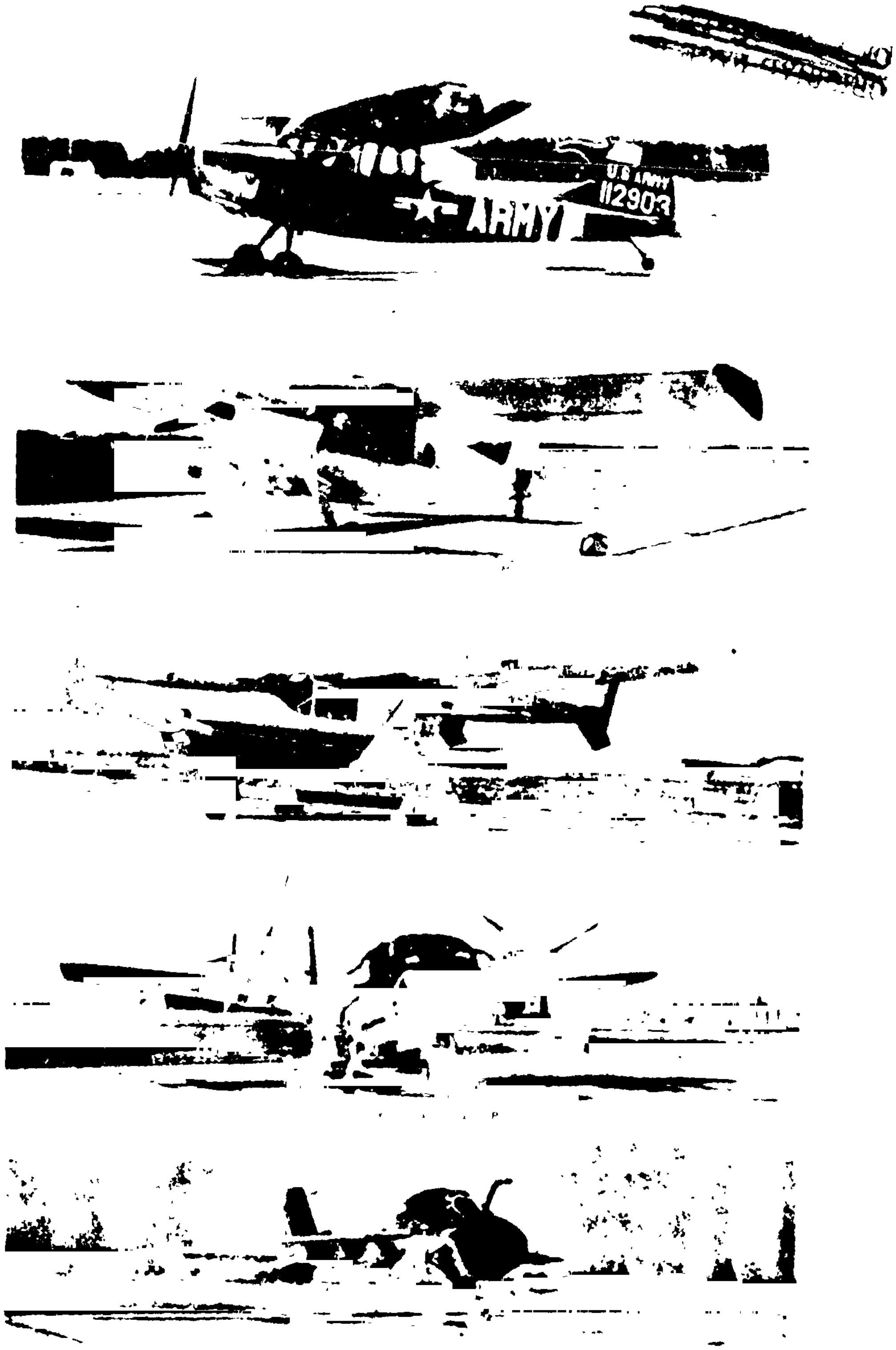
TABLE XI.-ESTIMATED AURAL DETECTION DISTANCE FOR THE A-6 AIRCRAFT, IN FEET FROM OBSERVER

FLIGHT CONDITION		BASIC A-6	MOD. I (4-LOBE SUPPRESSOR)	MOD. II (8-LOBE SUPPRESSOR)
ALTITUDE, FT	GROUND COVER			
300	18-IN. GRASS	13 000 [a] 3	9300 3	9800 3
	LEAFY JUNGLE	8400 3	6600 3	6900 3
1 000	18-IN. GRASS	22 700 3	15 100 3	16 400 3
	LEAFY JUNGLE	14 800 3	11 600 3	12 100 3

[a] DENOTES CRITICAL OCTAVE BAND



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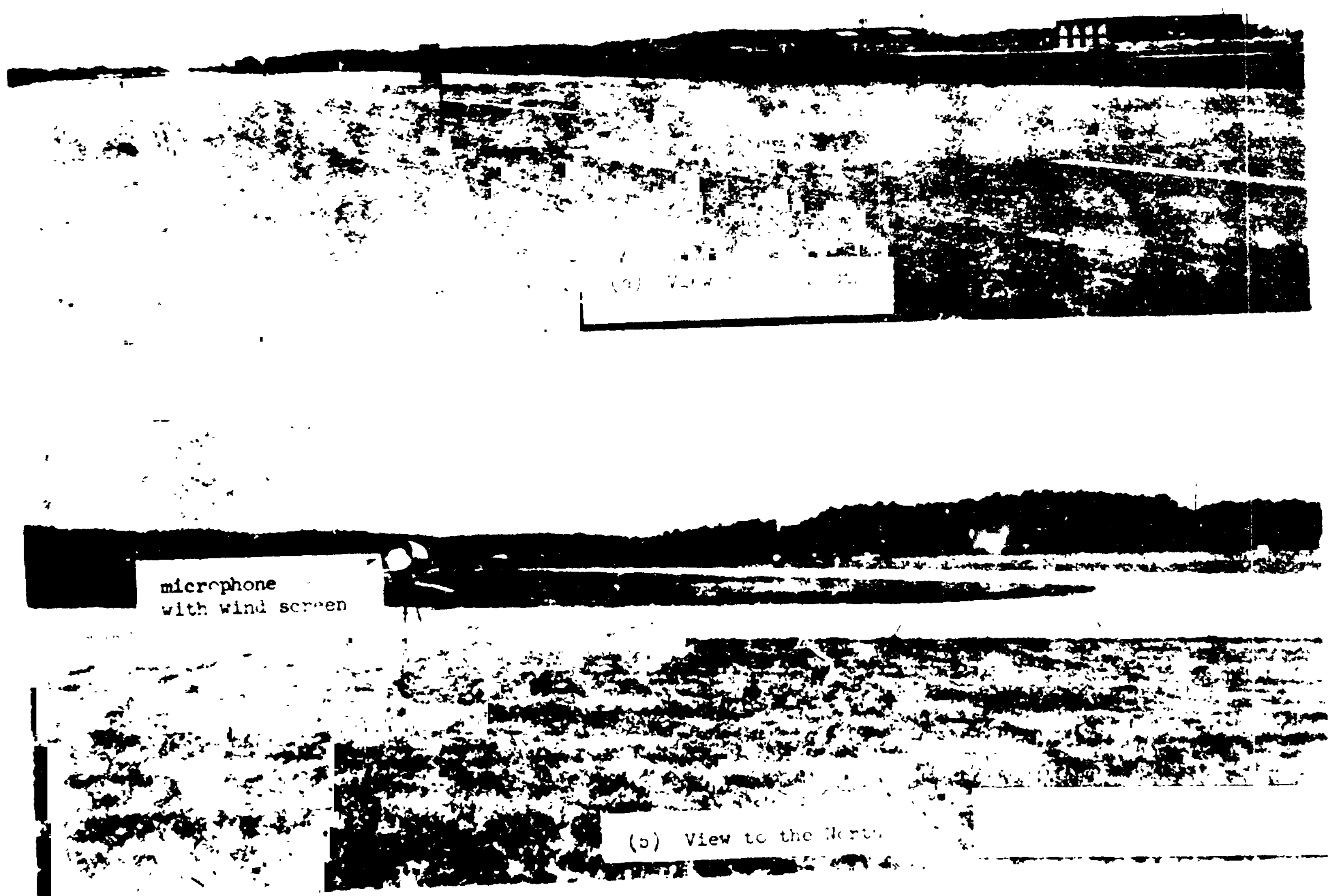
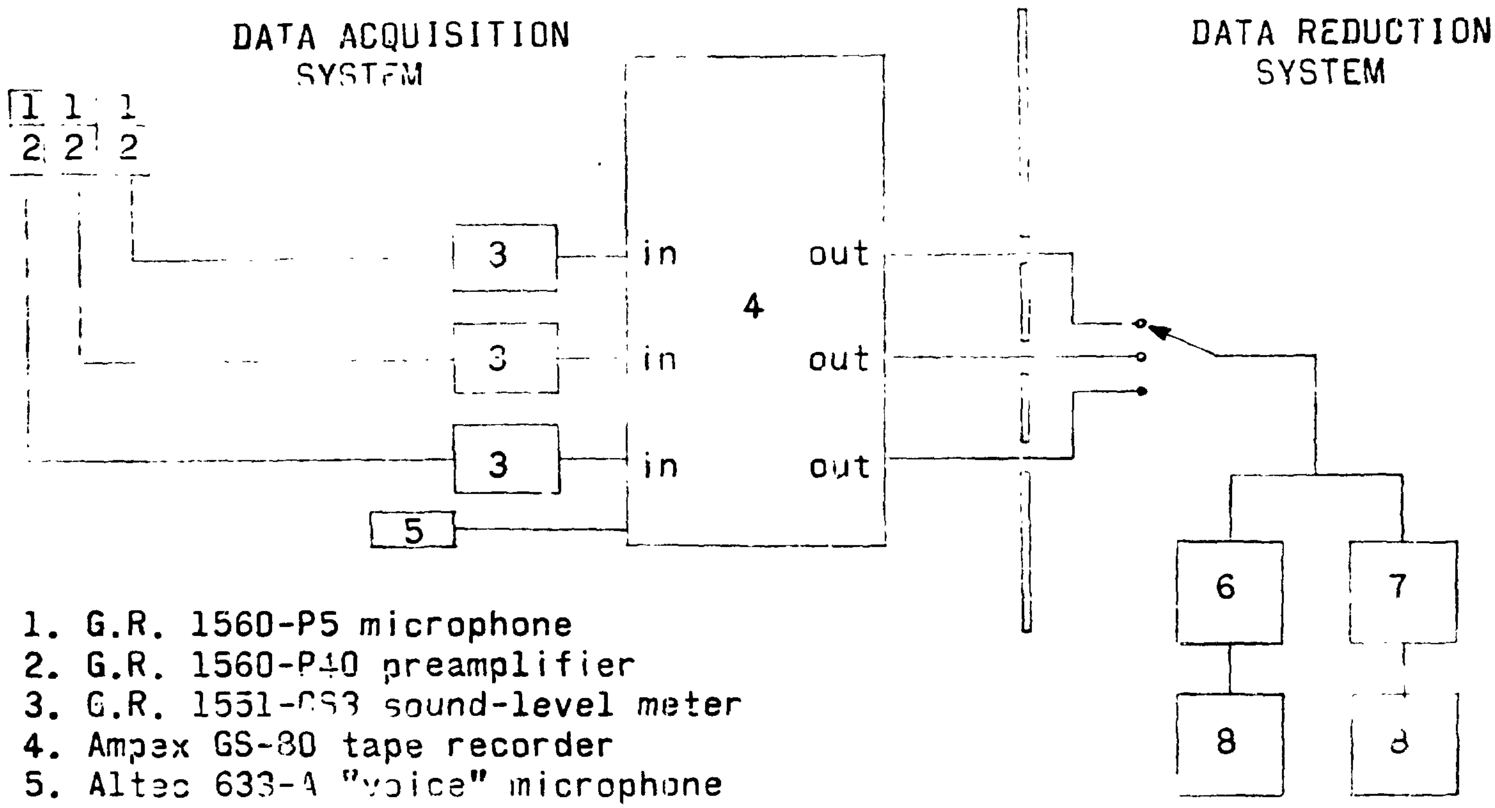
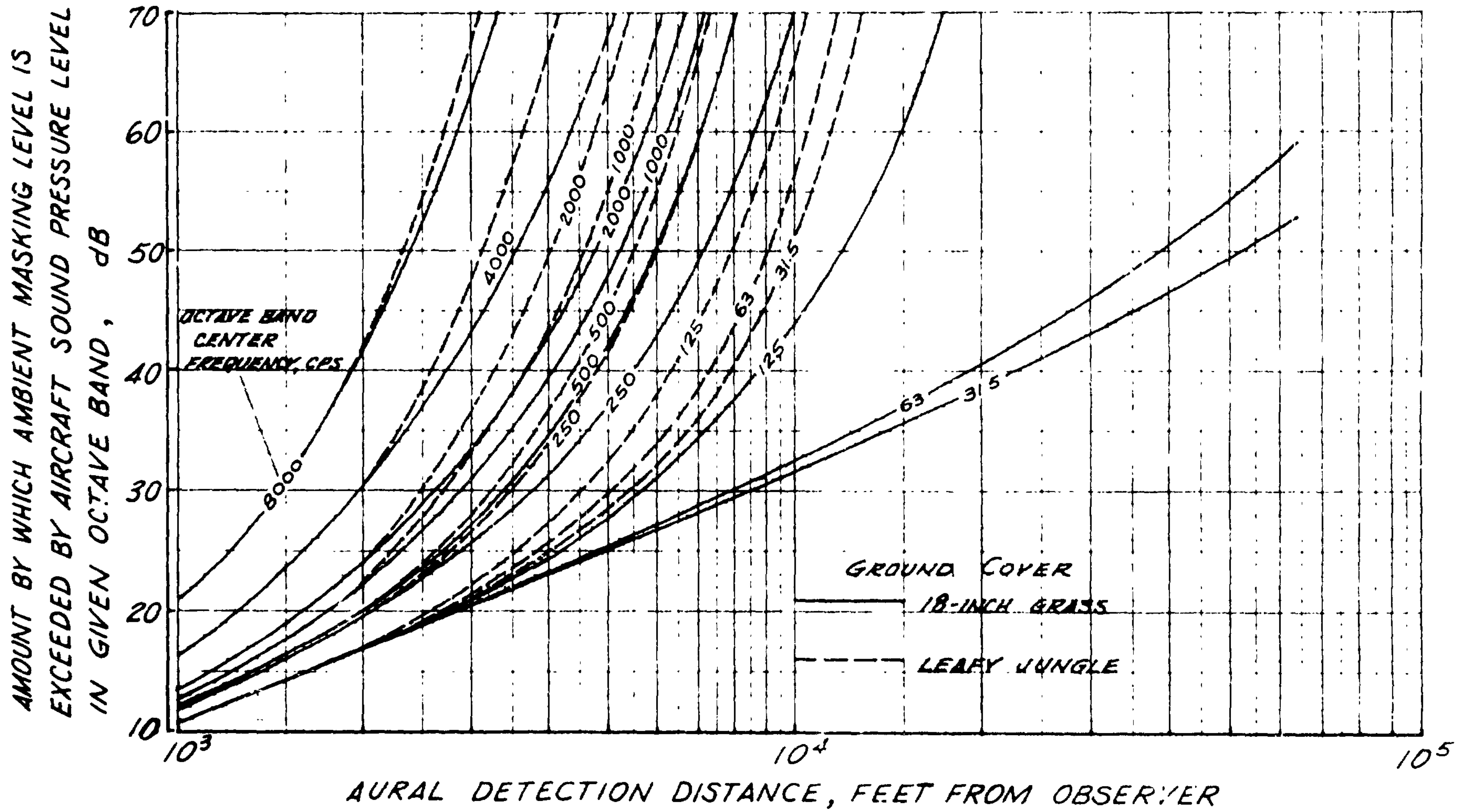


Figure .- Photographs of the NASA Wallops Island test area showing the runway and flat terrain.



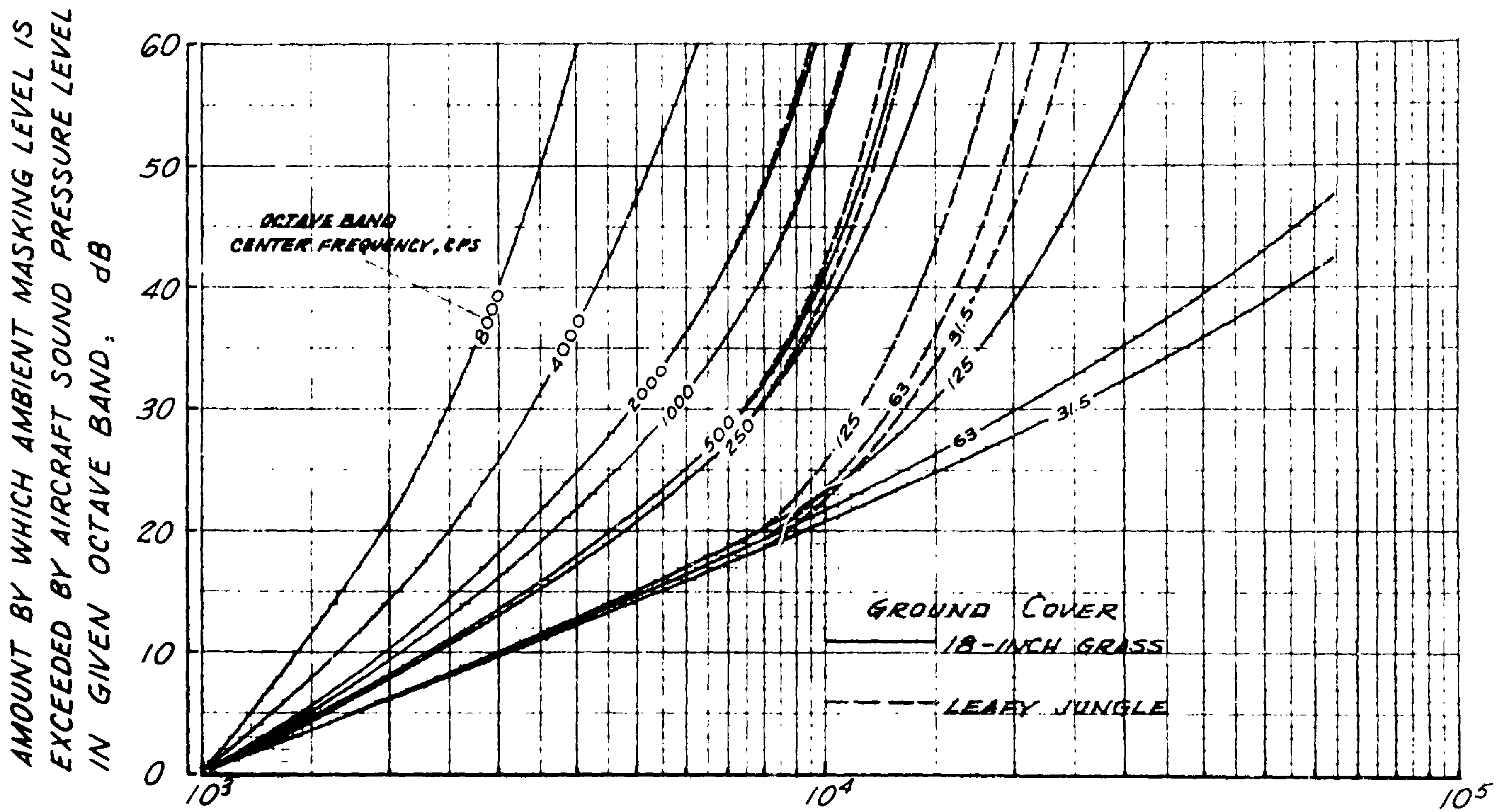
1. G.R. 1560-P5 microphone
2. G.R. 1560-P40 preamplifier
3. G.R. 1551-C sound-level meter
4. Ampex GS-80 tape recorder
5. Altec 633-A "voice" microphone
6. G.R. 1558-AP octave-band analyzer
7. G.R. 1900-A wave analyzer
8. G.R. 1521-B graphic level recorder

Figure 3.- Block diagram showing system layout for noise data acquisition and reduction.



(a.) 300 FT. ALTITUDE

FIGURE 4.- CHART FOR ESTIMATING THE AURAL DETECTION DISTANCE OF AN AIRCRAFT FLYING OVER TWO TYPES OF GROUND COVER.



(b.) 1000 FT. ALTITUDE

FIGURE 4.- CONCLUDED.

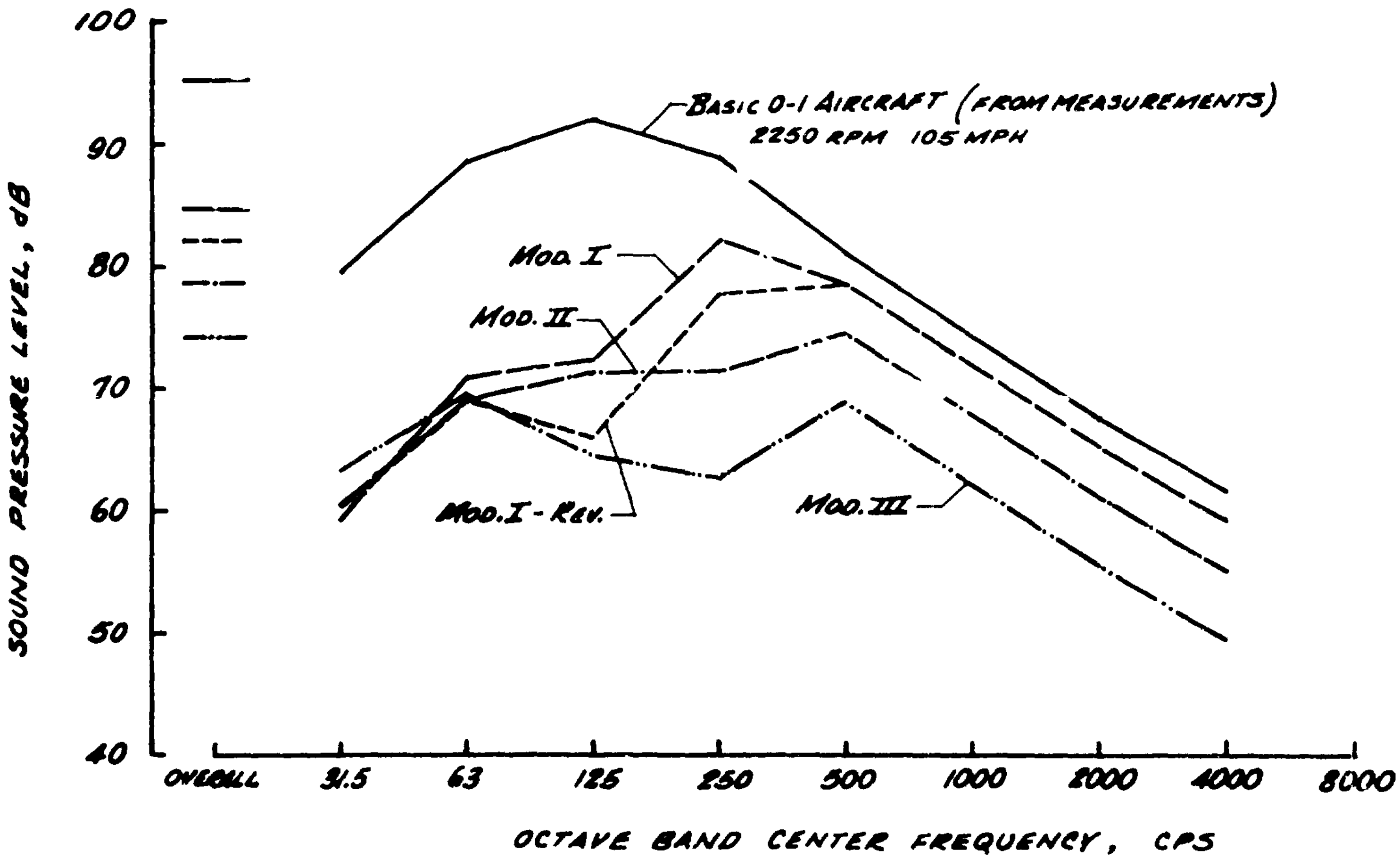


FIGURE 5. - DISTRIBUTION OF SOUND PRESSURE LEVEL IN THE VARIOUS OCTAVE BANDS FOR THE BASIC 0-1 AIRCRAFT AND THE MODIFICATIONS ANALYZED. DISTANCE = 300 FEET.

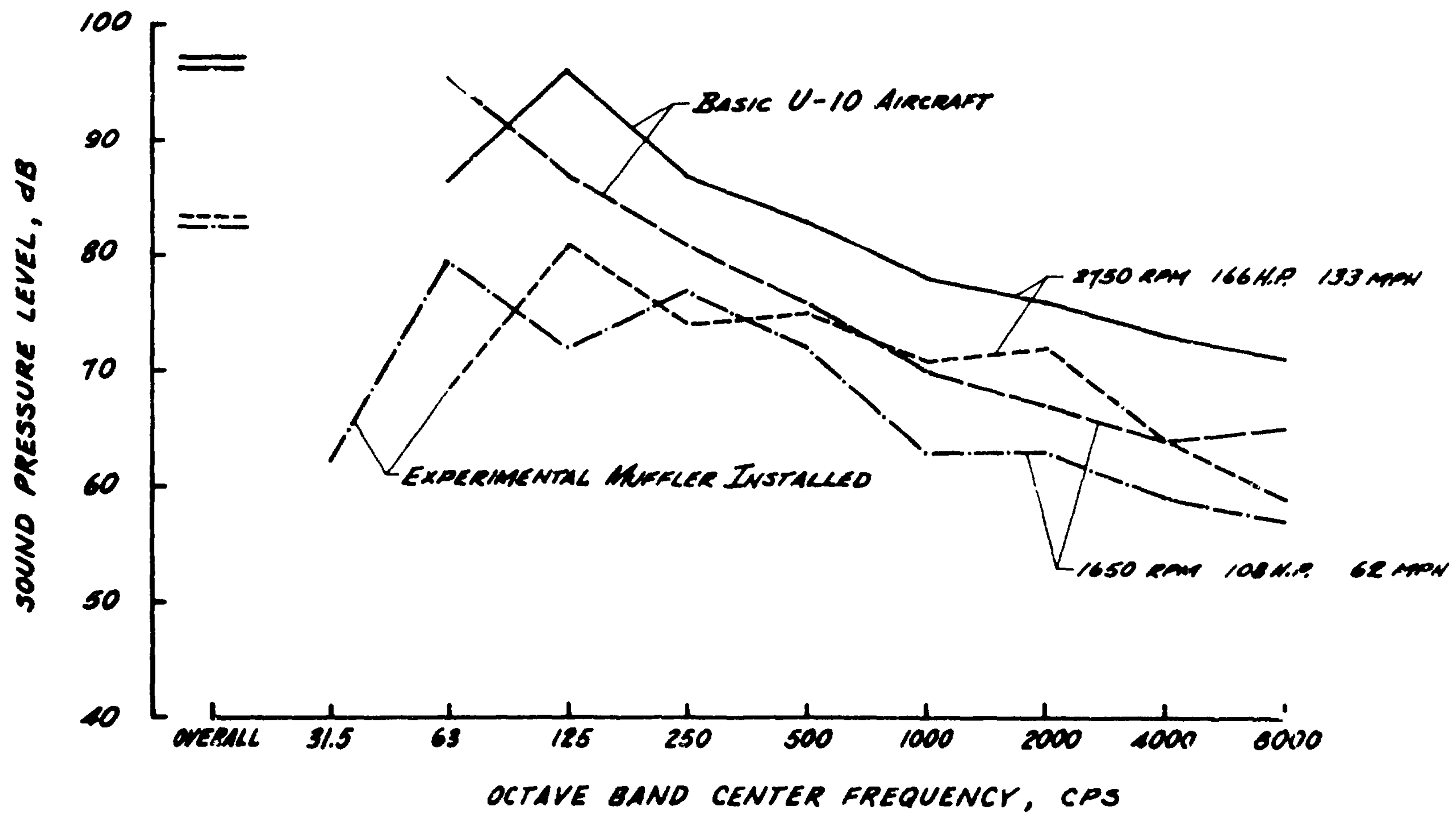


FIGURE 6.- DISTRIBUTION OF SOUND PRESSURE LEVEL IN THE VARIOUS OCTAVE BANDS MEASURED FOR THE U-10 AIRCRAFT WITH AND WITHOUT AN EXPERIMENTAL MUFFLER. DISTANCE = 300 FEET.

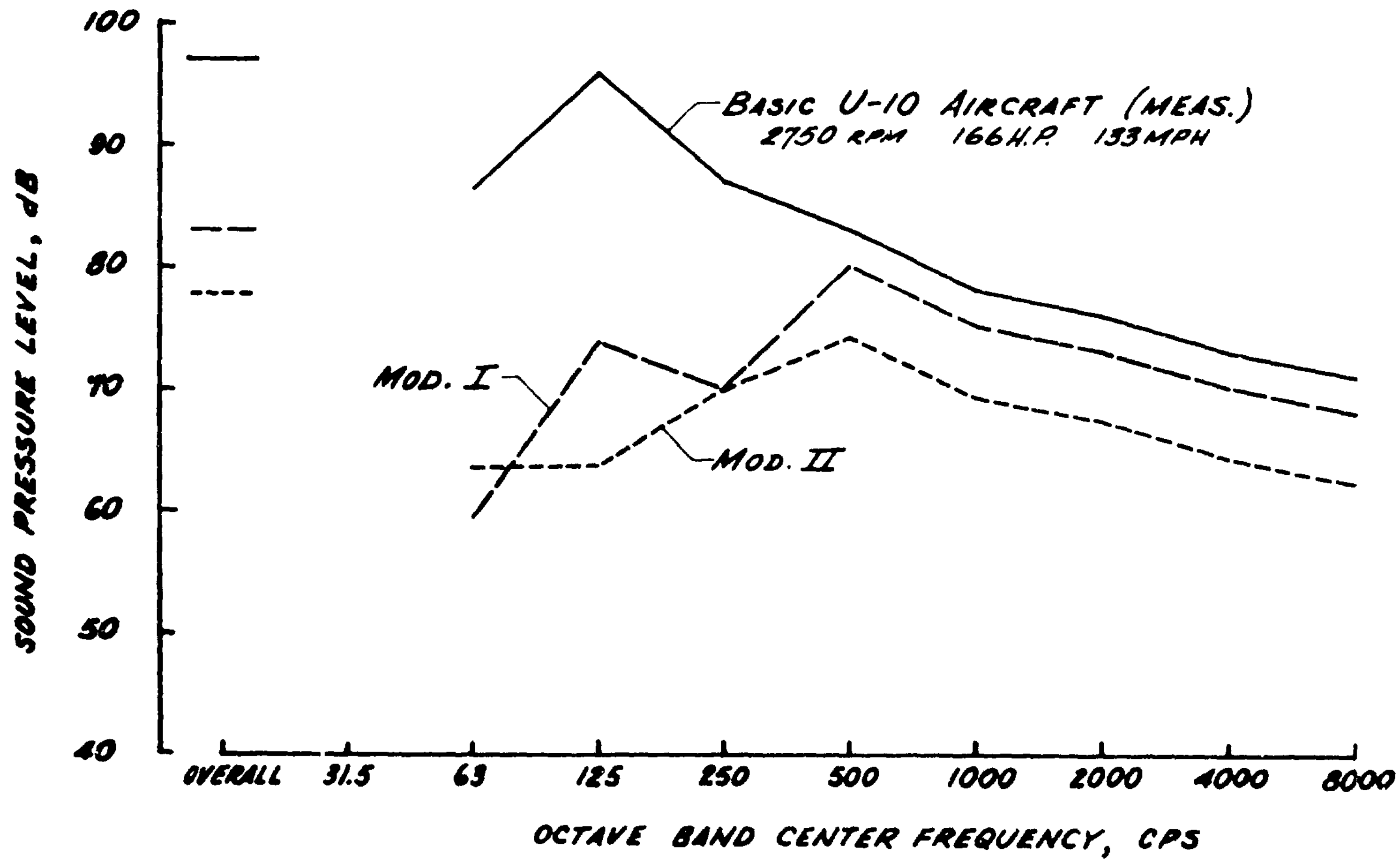


FIGURE 7.- DISTRIBUTION OF SOUND PRESSURE LEVEL IN THE VARIOUS OCTAVE BANDS FOR THE BASIC U-10 AIRCRAFT AND THE MODIFICATIONS ANALYZED. DISTANCE = 300 FEET.

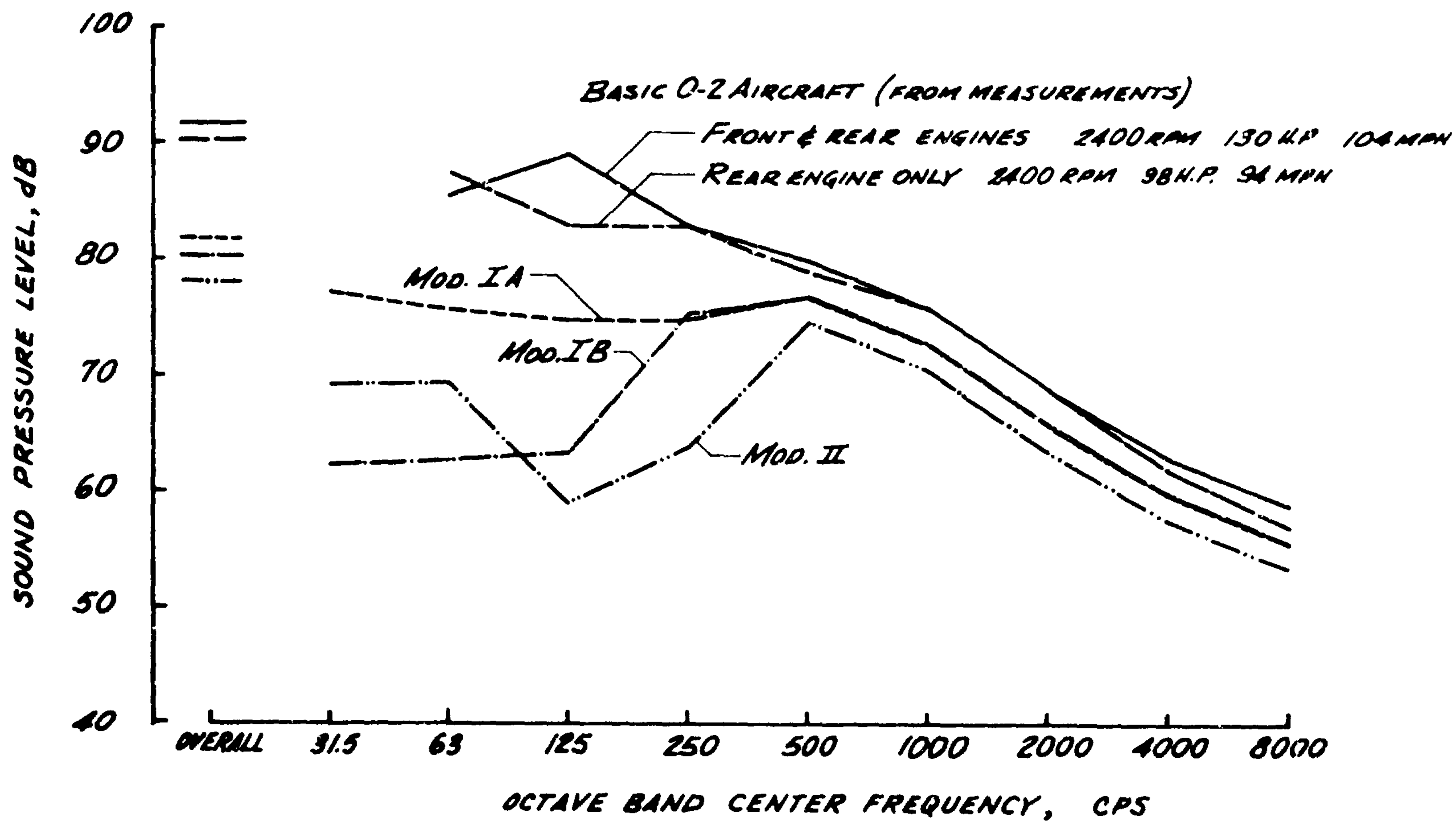


FIGURE 8 .- DISTRIBUTION OF SOUND PRESSURE LEVEL IN THE VARIOUS OCTAVE BANDS FOR THE O-2 AIRCRAFT (CESSNA MODEL 337) AND THE MODIFICATIONS ANALYZED. DISTANCE = 300 FEET.

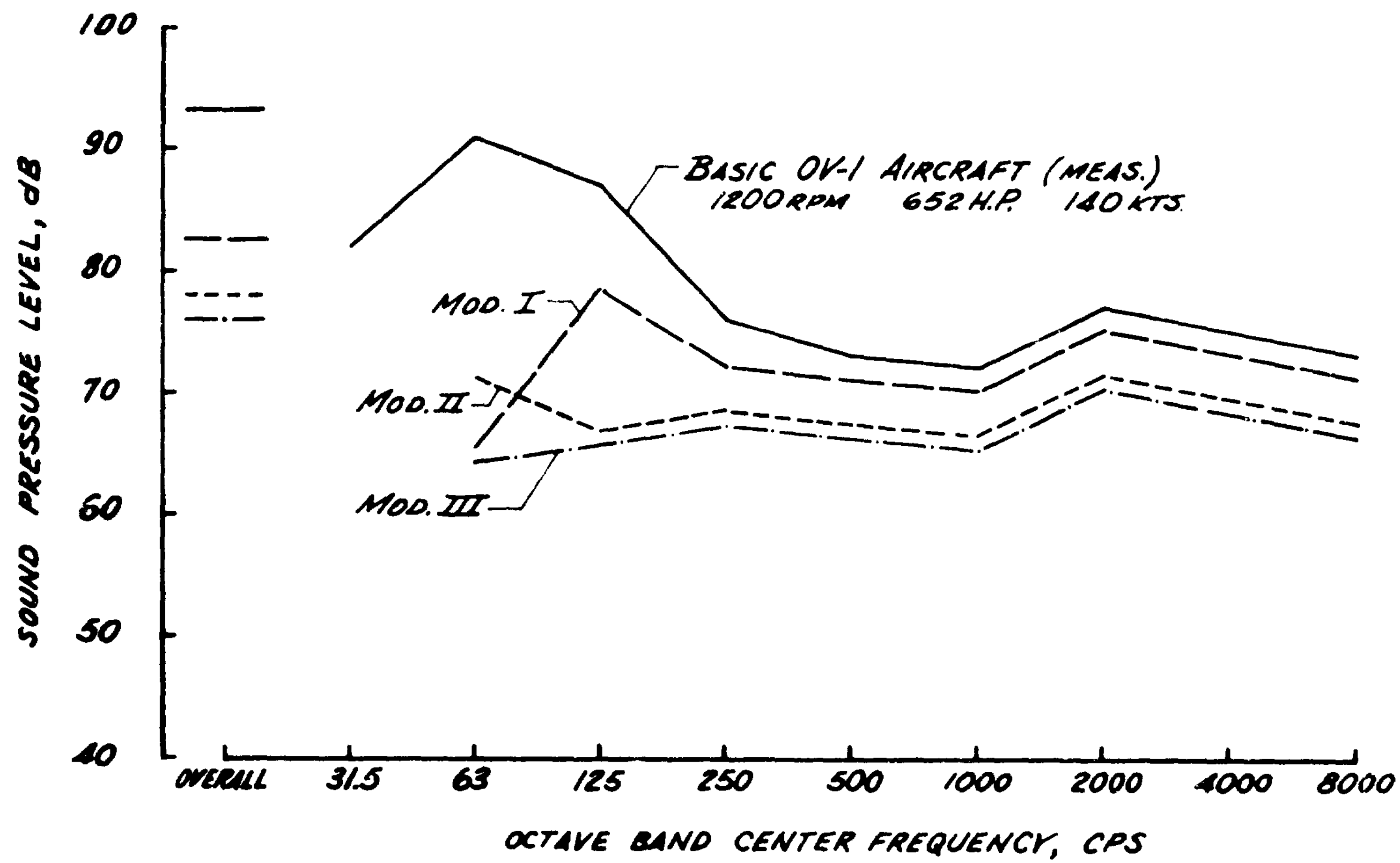


FIGURE 9.- DISTRIBUTION OF SOUND PRESSURE LEVEL IN THE VARIOUS OCTAVE BANDS FOR THE BASIC OV-1 AIRCRAFT AND THE MODIFICATIONS ANALYZED. DISTANCE = 300 FEET.

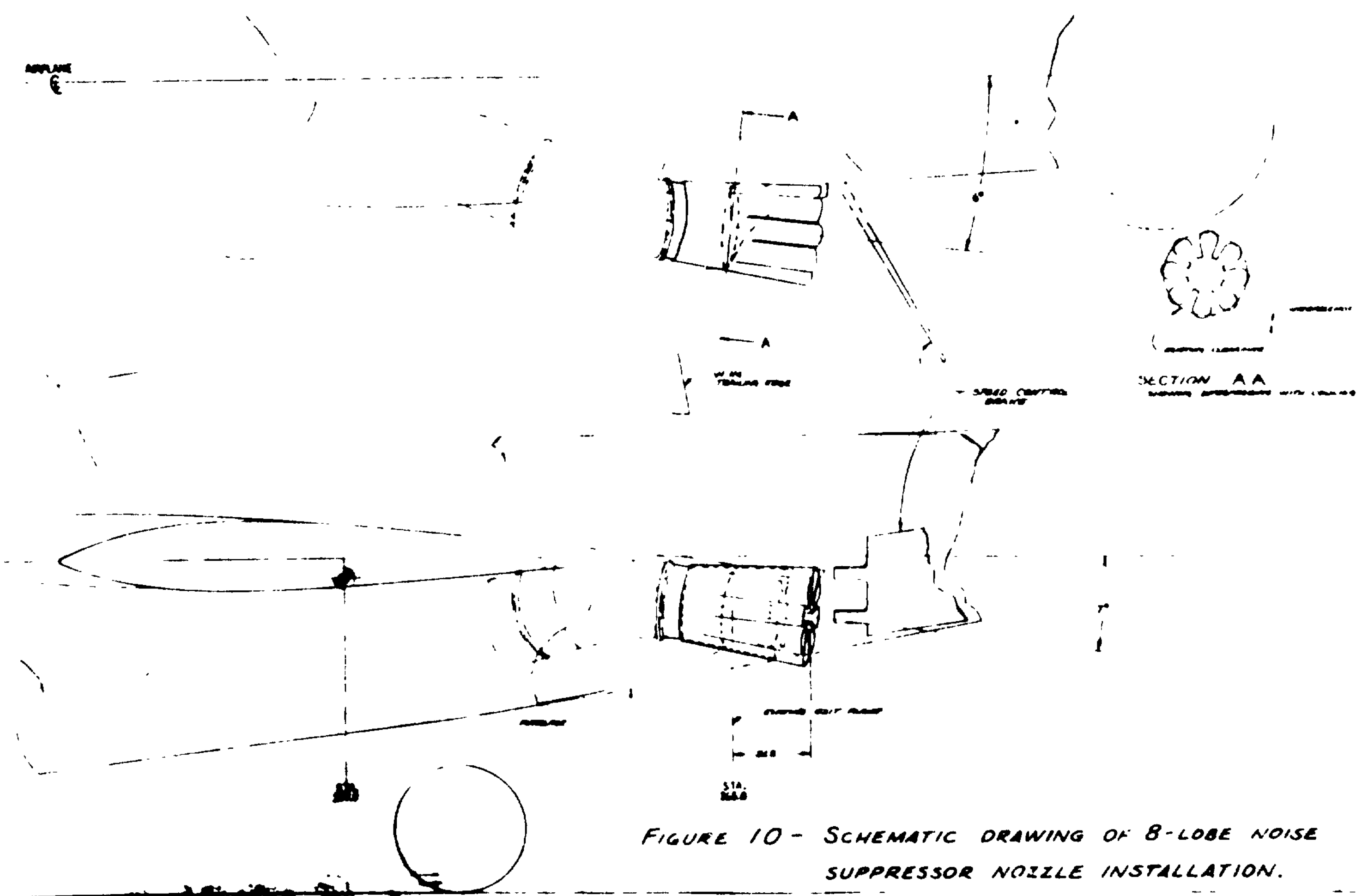


FIGURE 10 - SCHEMATIC DRAWING OF 8-LOBE NOISE SUPPRESSOR NOZZLE INSTALLATION.

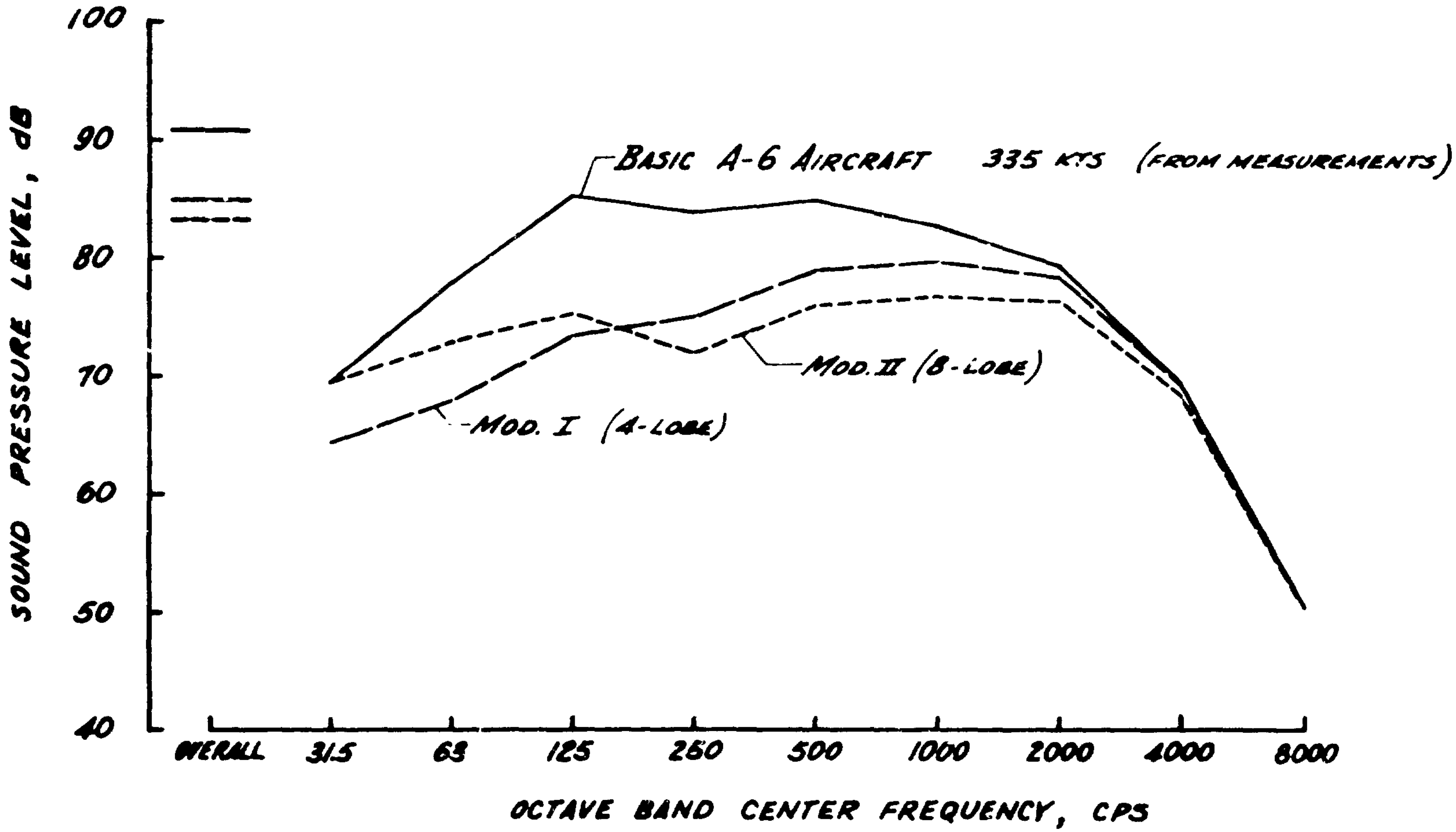


FIGURE 11.- DISTRIBUTION OF SOUND PRESSURE LEVEL IN THE VARIOUS OCTAVE BANDS FOR THE BASIC A-6 AIRCRAFT AND THE MODIFICATIONS ANALYZED. DISTANCE = 1000 FEET.